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Clean Electricity production by Solid Oxide Fuel Cell-Waste Heat Recovery Boiler arrangement in conjunction with a Gas Turbine

Clean Technology by Systems Integration

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***Abstract*— In this paper we have proposed a novel approach of generating electricity through the integration of 3 systems,viz., Solid Oxide Fuel Cell(SOFC), Gas Turbine and Waste Heat Recovery Boiler. An after-burner is incorporated between the gas turbine and WHRB. In case of a standard SOFC, the exhaust heat is unrecovered and is lost to the atmosphere in the form of the exhaust gases like CO_2 ,CO, H_2 and H_2O. The untapped hydrogen potential from the exhaust of the SOFC is then harnessed in the after-burner which provides the source of heat for the WHRB. In this literature we have obtained through calculations the electricity generated per unit mass of CO_2 emitted, thereby providing a theoretical overview of the above mentioned arrangement for cleaner electricity production. It is also accompanied by an addition in improved overall thermal efficiency than these individual systems.**

Keywords-Solid Oxide Fuel Cells (SOFC) ,Clean Technology, Gas Turbine, Waste Heat Recovery Boiler (WHRB), after-burner, hydrogen potential, thermal efficiency.

I. Introduction

In today's global scenario the issue that demands immediate attention is the uncontrolled emission of greenhouse gases. These greenhouse gases (GHG) have been primarily responsible for the rise in global temperature of the earth. The source of greenhouse gases today are not only limited to the exhaust of automobiles, chemical industries but also electricity generating plants such as coal fired thermal power stations and mainstream boilers. These conventional modes of electricity production use coal and other fossil fuels as their primary source of fuel for electricity production. The flue gases formed upon burning these fuels majorly comprise of greenhouse gases leading to temperature rise as a result of global warming. This calls for a cleaner and efficient technology that counters these immediate concerns.

Our systematic integration of the 3 individual systems of power generation viz.,SOFC,WHRB and Gas Turbine, presents an economically viable and technically practical solution to this demanding social concern. In this literature, we have substantiated our stand by delineating the various calculations involved in such an arrangement to generate electricity which accounts for lesser GHG emissions. By coupling the state-of-art technology with the conventional methods of power generation, we have presented here a first step towards a sustainable future.

II. System Arrangement

Our integrated system arrangement consists of SOFC, Gas Turbine, after-burner and WHRB in order of mention.

A. SOFC

We have incorporated a standard SOFC with YSZ (yttria stabilized zirconia) as electrolyte. The cathode of such a SOFC is Sr-doped $LaMnO_3$ while the anode being Ni-ZrO_2 cermet. The working temperature and pressure is 1100 K and 0.4 MPa. The stack arrangement contains 500 cells arranged in parallel to each other. The standard output of each stack is 0.7 V. The fuel at the inlet of this SOFC is taken as methane (CH_4) and the typical gases at the exhaust were observed to be a mixture of CO_2 ,CO, H_2 and H_2O. The CO observed at the exhaust is due to incomplete combustion of methane. There is a H_2 leakage in such an system due to the involvement of the water gas shift reaction which does not proceeds to completion rather is an equilibrium reaction. Thus, the amount of H_2 observed at the exhaust depends directly on the extent of completion of this reaction. The standard calorific value of H_2 is 120.971 MJ/Kg and that of CO is 10.112 MJ/Kg. This untapped potential of both CO and H_2 results as a loss of chemical energy of the input fuel, CH_4 at the exhaust thereby limiting the actual efficiency of the stand-alone fuel cell.

B. Gas Turbine

The gas turbine is attached directly to the exhaust line of the SOFC. Its blades are subjected to these exhaust gases whose pressure is used to rotate these blades to produce useful electricity. The gas turbine used for our arrangement is subjected to a pressure and temperature of 0.4 MPa and 1100 K respectively. These gases after passing through the turbine are then introduced into the after-burner.

C. After-Burner

To fully exploit the unused chemical energy of the exhaust from SOFC, we in our arrangement employ an after-burner. The main function of the after burner is to aid the combustion of remnant CO to completion to form CO_2 and also facilitate the formation of steam from combustion of leaked H_2 from the SOFC. An after-burner in our case is a simple device which supplies pure oxygen at ambient pressure and temperature conditions. The products of combustion would thus be CO_2 and steam. The exhaust from the after-burner is then directed to the WHRB for sensible heat exchange.

D. WHRB

The Waste Heat Recovery Boiler system comprises of the following components: Boiler, Steam Turbine, Condenser and Pump in order.

1. *Boiler* :

This is the steam producing component of the WHRB arrangement. The products of combustion of the after-burner are made to flow in tubes into the boiler containing water at a pre-calibrated flow rate.

The boiler acts as a heat exchanger between the gases in the tube and the tube thereby leading to formation of steam in the boiler drum. The steam in our arrangement is produced at 823K and at 150 bar at the calculated steam production rate corresponding to the heat exchange facilitated in the boiler.

2. *Steam Turbine* :

It is the prime mover of the WHRB. The steam produced in the boiler then rotates this turbine thus generating electricity in the generator which is coupled to the turbine. The input conditions to the turbine in our arrangement are 823 K and 150 bars.

3. *Condenser* :

The steam from the steam turbine enters the condenser at 318.8K.The condenser in our arrangement is maintained at 0.1 bar.

4. *Pump* :

The pump employed is used to deliver water from the condenser outlet to the boiler with an accompanied rise temperature and enthalpy.

III. NOMENCLATURE

n	number of moles per hour
C_p	specific heat at constant pressure
γ	ratio of specific heats
T	absolute temperature
p	pressure
m	mass
h	enthalpy
v	specific volume
χ	dryness fraction
F	Faraday's constant
i	current
V	voltage
W	work
Q	heat
P	power
s	entropy
w_s	mass flow rate of steam
T_{pp}	pinch point temperature
η	efficiency
k	equilibrium constant of reaction
x	extent of reaction
CV	Calorific value of fuel

IV. CALCULATIONS AND TABLES

A. SOFC

$CH_4 + 2\,H_2O \rightarrow 4\,H_2 + CO_2$ (Steam Reforming Reaction)

$H_{2,anode} + (½)O_{2,cathode} \rightarrow H_2O_{,anode}$ (Fuel Cell Reaction)

$CO + H_2O \leftrightarrow CO_2 + H_2$ (Water Gas Shift Reaction)

Assuming 80% fuel utilization and that methane is completely reformed within the fuel cell.

n_{CH4} supplied = 100 moles/hr

n_{CH4} utilized = (0.80*100) = 80 moles/hr

Considering the water gas shift reaction,

$$k= [CO_2]\ [H_2] / [CO][H_2O]$$

Taking the extent of reaction into consideration,

$$k= [CO_2+x][H_2+x] / [CO-x][H_2O-x]$$

$$k[CO-x][H_2O-x] = [CO_2+x][H_2+x]$$

$$(1-k)\ x^2 + \{[CO_2]+[H_2]+k([CO]+[H_2O])\}x+ \{[CO_2][H_2]-[CO][H_2O]k\} = 0$$

Comparing with standard quadratic equation, $ax^2 + bx +c=0$

$$a = (1-k)$$
$$b = \{[CO_2]+[H_2]+k([CO]+[H_2O])$$
$$c = \{[CO_2][H_2]-[CO][H_2O]k\}$$

The solution of this equation is $x = \{-b \pm \sqrt{(b^2 - 4ac)}\}/2a$

From Vant Hoff's equation, $k = e^{(4276/T - 3.961)}$

In SOFC, T = 1100 K

On calculation, k = 0.9289, a= 0.071, b= 0.9711, c= 0.0888, x= -0.092 or 13.58.

But the only possible value of x is -0.092.

In a fuel cell, $H_2 \rightarrow 2H^+ + 2e^-$

For every mole of H_2 consumed, 2 moles of electron are formed and each electron carries an electric charge of 96,487 C.

Thus, for production of 1 A current, 0.037605 kg /hr-kA of H_2 is required. This value serves as a standard conversion factor for our problem statement.

From tables, In fuel cell reaction,
n_{H2} consumed = (80*4) + 26.66-17.46= 329.2 moles/hr
m_{H2} consumed = 329.2*2.015 =663.52 g/hr = 0.66352 kg/hr

$$m_{H2} = I*0.037605 \quad [2]$$
$$I = 17.64 \text{ kA}$$

P=V*I , V = 0.7V standard for stacks in parallel

$$P_1 = 12.35 \text{ kW} \quad (1)$$

B. Gas Turbine

From table, n_{H2O}= 147.6, n_{H2}= 52.38, n_{CO2} =72.39,n_{CO} =27.6

At turbine inlet, T_2 = 1100K and P_2 = 4 bar
At turbine outlet, P_1 = 1 bar
γ_{CO2} = 1.28, γ_{H2O}=1.33, γ_{CO}=1.4, γ_{H2}=1.405

$$\gamma_{mix} = [(\gamma_{CO2} * n_{CO2})+(\gamma_{CO} * n_{CO})+(\gamma_{H2O} * n_{H2O})+(\gamma_{H2} * n_{H2})] /100 = 1.337$$

$$(P_2/P_1)^{(\gamma-1)/\gamma} = (T_2/T_1), \quad T_1 = 775.6K$$

Change in Enthalpy = Work done by turbine =
$(n_{H2O}*C_{pH2O} + n_{CO2}*C_{pCO2} + n_{H2}*C_{pH2} + n_{CO}*C_{pCO})*dT$

C_{pH2O} = 8.22 + 0.00015*T+ 0.00000134*T^2 cal /K/mol [1].
C_{pCO} = 6.6 + 0.0012*T cal/K/mol [1].
C_{pH2} = 6.62 + 0.00081*T cal/K/mol [1].
C_{pCO2} = 10.34 + 0.00274*T – 195500 / T^2 cal /K/mol [1].

Total Work done = 1305.19 kJ/hr
Total Power produced = 1305.19/3600

$$P_2 = 0.3625 \text{ kW} \quad (2)$$

C. After-burner

At T=775.6 K,

C_{pH2O} = 38.21 J/K/mole, C_{pCO} = 31.47 J/K/mole,
C_{pCO2} = 50.74 J/K/mole, C_{pH2} = 30.297 J/K/mole.

At T=T_3 K,

C_{pH2O} = 8.22+.00015T+0.00000134T^2 cal/K/mole
C_{pH2O} = 10.34+.00274T-195500/T^2 cal/K/mole

Applying Energy Balance equation ,

$$(n_{H2O}*C_{pH2O} + n_{CO2}*C_{pCO2} + n_{H2}*C_{pH2} + n_{CO}*C_{pCO})*T_1 + (n_{CO}*CV_{CO} + n_{H2}*CV_{H2}) = (n_{H2O}*C_{pH2O} + n_{CO2}*C_{pCO2})*T_3$$

The fresh oxygen required to complete the combustion is taken at ambient conditions. Thus, CV_{O2} = 0 (reference)
CV_{CO} = 283 kJ/mol [1] , CV_{H2} = 243.863 kJ/mol [1].

On Solving, T_3 = 1800K(approx.)

The exhaust after combustion consists of CO_2 and H_2O only.

D. WHRB

At T = 1800 K,
C_{pCO2} = 63.58 J/K/mol, C_{pH2O} = 53.636 J/K/mol
Standard T_{pp} = 455K [2] for a gas turbine.

Now, n_{CO2} = 72.39 + 27.6 = 100, n_{H2O} = 147.6+52.38 = 200
It is required to produce steam at 823 K and 150 bars at the boiler of WHRB.
Considering condenser pressure = 0.1 bar, T_{sat} = 318.8K
For these conditions, (from steam tables)

Enthalpy of steam at turbine inlet, h_1 = 3448.60 kJ/kg
Enthalpy of steam at turbine outlet, h_2 = 2059.90 kJ/kg
Enthalpy of water at condenser outlet, h_3 = 191.8 kJ/kg
Enthalpy of water at boiler inlet, h_4 = 191.95 kJ/kg

$$w_s = \{(C_{pCO2}*n_{CO2} + C_{pH2O}*n_{H2O})*(T_3 - T_{pp})\}/\{(h1-h4)*1000\} = 2.35 \text{ kg/hr}$$

work done by turbine, $W_t = w_s*(h_1 - h_2)$ = 3263.445 kJ/hr
heat addition to boiler, $Q_1 = w_s*(h_1 - h_4)$ = 7653.127 kJ/hr
work done by pump, $W_p = w_s*(h_4 - h_3)$ = 0.3525 kJ/hr

Power generated in steam turbine = 3263.445/3600

$$P_3 = 0.9065 \text{ kW} \quad (3)$$

E. Overall System

Total power produced = $P_1 + P_2 + P_3$

$$P = 13.619 \text{ kW} \quad (4)$$

CV_{CH4} = 55.6 kJ/g
Mass of input CH_4 = 100*16.043 = 1604.3 g/hr
Total input energy = 1604.3*55.6/3600 = 24.77 kW (5)

Overall system Efficiency, η = P*100/ input
= 13.619*100/24.77
= 55%

Total mass of CO_2 produced = (100*44)/1000 = 4.4 kg/hr
Thus (13.619*3600/4.4) = 11.1 MJ of energy is generated with 1 kg of exhaust CO_2.

TABLE I. COMPOSITIONS BEFORE WATER GAS SHIFT REACTION

Gas	FC inlet (mol %)	FC inlet (mol/ hr)	Ref/ FC rxn (mol/ hr)	Refor ming (mol/ hr)	FC outlet (mol/ hr)	FC outlet (mol %)
CH_4	100	100.0	-80	-20	0.0	0.0
CO	0.0	0.0	0.0	0.0	0.0	0.0
CO_2	0.0	0.0	80	20	100	33.33
H_2	0.0	0.0	0.0	80	80	26.66
H_2O	0.0	0.0	160	-40	120	40
Total	100.0	100	160	40	300	100

(-)negative sign implies that the component is being consumed.

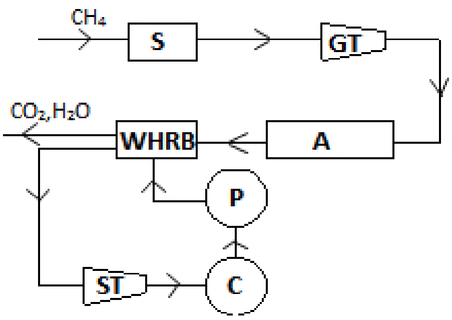
TABLE II. COMPOSITIONS AFTER WATER GAS SHIFT REACTION

Gas	FC outlet w/o shift (mol %)	FC outlet w/o shift (mol/hr)	Effect of Shift rxn (mol/hr)	FC outlet in Shift equil (mol/hr)	FC outlet in Shift equil (mol %)
CO	0.0	0.0	9.20	9.2	9.2
CO_2	33.33	33.33	-9.20	24.13	24.13
H_2	26.67	26.67	-9.20	17.46	17.47
H_2O	40	40	9.20	49.2	49.2
Total	100	100	0.0	100	100

(-) negative sign implies that the component is being consumed.

FIGURE I. Integrated System Arrangement

[1] GT-Gas Turbine, ST-Steam Turbine, P-Pump C-Condenser, A-After Burner, S-SOFC



V. CONCLUSION AND FUTURE WORK

Thus such an arrangement as shown above is capable of generating clean energy without the extensive use of greenhouse gases as 11.1 MJ of energy is developed per Kg of CO_2 emitted. Such an arrangement is practically possible and is economically viable as shown by the calculations (with reference to the achieved temperature and pressure at every stage).

There are several other arrangements possible within these 3 systems and integration of more than 3 systems is also possible. In this literature we have taken the example of one such possible system to show that such an arrangement could possibly be used in practice for production of electricity. We in future would experiment on integration of more complex systems at varying conditions in order to achieve higher efficiencies for the same given input.

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